ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOP003

OPTIMAL DESIGN AND FLUID-SOLID COUPLING THERMAL ANALYSIS OF SC200 SUPERCONDUCTING PROTON CYCLOTRON ELECTROSTATIC DEFLECTOR

Yue Xu[1], Kaizhong Ding[2,†], Xiongyi Huang[2], Kun Pei[2,3], Kangxin Gu[3], Junjun Li[2], Yuntao Song[2], Yonghua Chen[2,3]
[1]Anhui University, Hefei, Anhui, China
[2] Institute of Plasma Physics Chinese Academy of Science, China
[3] Hefei CAS Ion Medical and Technical Devices Co. Ltd., Hefei, China

Abstract

In recent years, the study of proton therapy equipment has received increasing attention in China. Hefei CAS Ion Medical and Technical Devices Co., Ltd. (HFCIM) is developing a proton medical device based on the superconducting proton cyclotron. The electrostatic deflector (ESD) is the key extraction component of the SC200 superconducting cyclotron, which uses a high-intensity electric field to bend the beam from the track. The fierce interaction between the proton beam and the deflector septum, causes a great loss of beam and unwanted excess heat accumulation and radiation. In order to minimize the risk of damage caused by the proton beam loss, the fluid solid-thermal coupling analysis of the deflector was performed by applying computational fluid dynamics (CFD) on ANSYS. The maximum temperatures of the septum in various cases of the cooling water speed, the septum thickness and material have been investigated respectively. The result based on analysis provide a valuable reference for the further optimization on the material selection and structural design for ESD.

INTRODUCTION

In modern society, the incidence of cancer has increased year by year. Proton therapy is becoming one of the main methods of cancer treatment because the proton beam provides superior dose distribution at several anatomical sites [1]. In recent years, proton therapy has received increasing attention in China and has made progress on a number of key technologies. Against this background, HFCIM is developing a proton medical device based on superconducting proton cyclotron (SC200). The extracted proton beam energy is designed to be 200 MeV and the beam current is higher than 400 nA. The proton beam extraction uses a precessional extraction method. The electrostatic deflector (ESD) is the first extraction element in the extraction system of the SC200 superconducting cyclotron, which uses a high-intensity electric field to strip the beam from the orbit.

Figure 1 shows the diagram of SC200 extraction system. In a cyclotron, the beam may be deposited at the extraction radius due to the extremely small turn separation. ESD cannot peel off the last turn without affecting the internal turns and the beam loss is much less, which is very difficult. Therefore, the thickness of the septum must be as thin as possible, and the specification range is 0.1 - 0.5 mm. The deposited beam energy is the most important risk of destroying ESD, and its performance directly affects the beam parameters. This paper mainly discusses the structural design and fluid-solid coupling thermal analysis of electrostatic deflector, and provides a valuable reference for further optimization.

† kzding@ipp.ac.cn

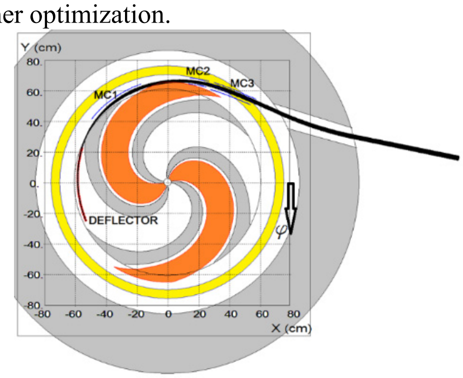

Figure 1: Schematic diagram of SC200 extraction system.

DESIGN AND SIMULATION

Simulation Model

The main structure of the electrostatic deflector is shown in Fig. 2. The septum is an integration design that is directly attached to the housing and has a thickness of only 0.1 mm. The outer surface of the septum is grooved, and the cooling water pipe is brazed in the groove to achieve the best cooling effect.

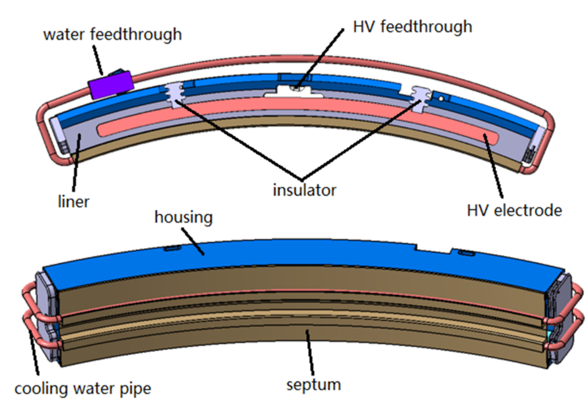

Figure 2: Main structure of ESD.

It is assumed that the beam loss rate at the entrance of the electrostatic deflector is 60%, which means that the

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOP003

deposition energy on the septum is 48 W. According to the Italian INFN research on the mechanism of breakdown, all materials of ESD have an effect on breakdown [2]. Because the high voltage electrode is loaded with a high voltage of -60 kV, we also care about the sparking phenomenon in the vacuum chamber. Therefore, in order to reduce the effects of thermal and sparking phenomena, we focus on structural optimization and material selection of electrostatic deflector. The main materials are listed in Table 1.

Table 1: Materials of Main Parts of ESD.

Part	Material
HV electrode	Titanium alloy
Septum	OFC
Liner	Stainless steel
Housing	Stainless steel
Insulator	Alumina ceramic

Simulation Calculation

The fluid-solid thermal coupling analysis of ESD is simulated by finite element analysis software ANSYS 17.2. It is known from previous experience that most of the beam loss is at the entrance of the septum [3]. And because the thermal conductivity of the septum is limited, heat will only accumulate near the entrance [4]. In order to simplify the calculation, the 1/4 length of the electrostatic deflector is used as a simulation model. The water cooling tube is brazed to the groove of the septum. The simulation model is shown in Fig. 3.

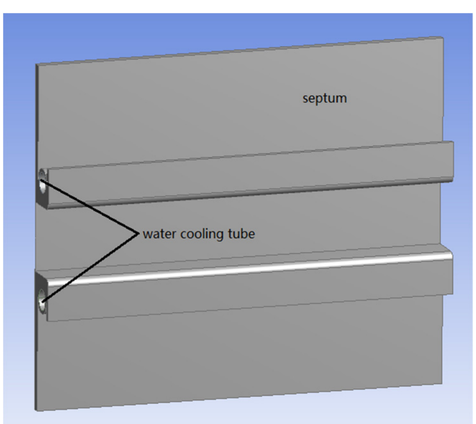

Figure 3: Simulation model in CFX.

It is approximated that the heat flux input Q at the entrance of the septum is Gaussian on the inlet surface. The Gaussian distribution equation is as follows:

$$Q = qe^{\frac{-x^2}{2\sigma^2}} \quad (1)$$

where q is a constant. The value of σ depends on the beam cross-section size, which is calculated by beam analysis to obtain σ = 3 mm. However, in actual operation, the relative position of the beam and the septum may change, and the area where the beam loss is also changed. In this limit condition, the load is all loaded on the surface of the 0.1 mm thick septum.

The total thermal power P is as follows:

$$P = \int Q\,sds = \sum_i^n Q(i)s(i) = \sum_i^n Q(i) * \Delta a(i) * b \quad (2)$$

where; i = 0, 1, ..., 9, Δa (i) = 0.25 mm, and b is the thickness of septum, b = 0.1 mm. P = 48 W for calculating the limit conditions.

The heat flux input of the Gaussian distribution as shown in Fig. 4 is distributed in the area shown in Fig. 5.

Both the septum and the water cooling tube are made of oxygen-free copper. Heat transfer is selected for each contact surface [5]. The boundary conditions at the inlet are set to a uniform temperature of 25 °C. The cooling water at 25 °C has a uniform water flow speed of 1 m/s. The outlet is set to 0Pa static pressure. The cooling water in the two water pipes flows to the same direction. The k-epsilon turbulence model is chosen for this analysis because it is suitable for most engineering conditions and provides better performance in terms of mathematical equations and precision. The solution strategy selects "Upwind", first-order discrete format. When the turbulent flow energy and heat transfer are less than 1×10^{-5}, the calculation is considered to be convergent.

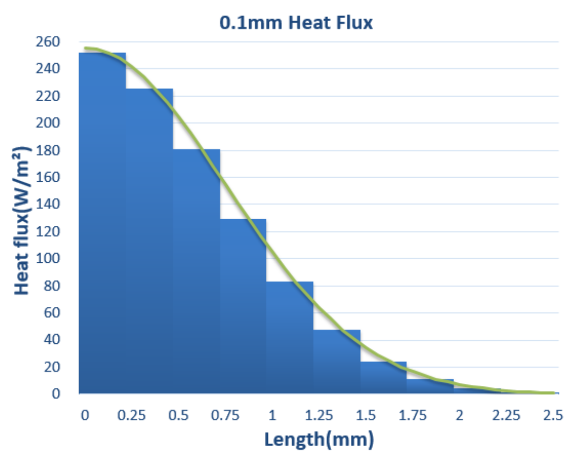

Figure 4: Input heat flux on surface of the septum.

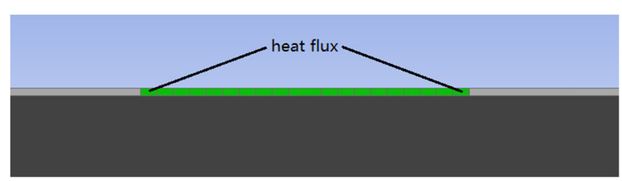

Figure 5: Input heat flux on surface of the septum.

SIMULATION RESULTS

Figure 6 shows the temperature distribution of the model under the conditions of an oxygen-free copper septum thickness of 0.1 mm, a cooling water flow speed of 1 m/s, and a beam loss power of 48 W. The results show that heat is mainly distributed around the heat source. The maximum temperature of 1027 °C appears at the center of the heat flux input, very close to the melting point of material. The septum is fixed to the housing, so the upper and lower ends are fixed. The septum is thermally deformed by being

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOP003

heated by the beam current to produce a protrusion of 0.11 mm, as shown in Fig. 7. This will cause more beam loss and heat accumulation, which worsens the problem. So the result is unacceptable.

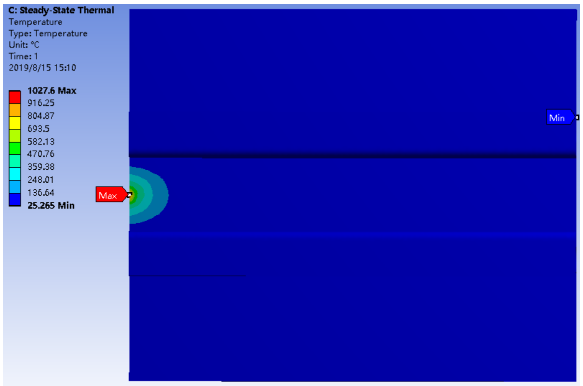

Figure 6: Temperature distribution of the model.

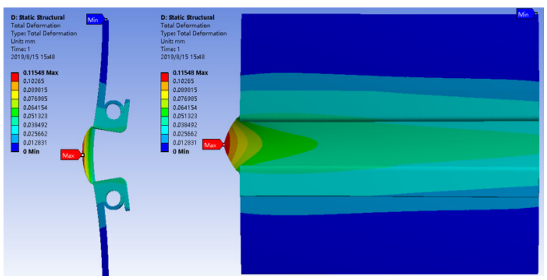

Figure 7: Structure deformation of the simulation model.

In order to reduce the thermal deformation, we consider the following points:

Material For the performance of the septum, perhaps a material with a higher melting point and heat transfer coefficient is more suitable. Table 2 lists the simulation results for several common dicing film materials. The thickness is 0.1 mm, the cooling water flow speed is 1 m/s, and the thermal power is 48 W.

Table 2: Simulation Results for Each Material

Material	Tmax (℃)	Δmax (mm)
OFC	1027.6	0.115
Mo	2764.3	0.082
Ta	6778.8	0.417
W	2184.6	0.058

From the point of view of temperature and deformation, tungsten is perhaps the best septum material.

Thickness The thinner the cut film thickness, the less the beam loss. However, the thickness also affects the heat transfer and de-formation of the septum. Under the conditions shown in Fig. 4, we believe that for every 0.1 mm increase in thick-ness, the beam will lose 10% more. The maximum temperature T and the maximum deformation ε of septa of different thicknesses were calculated. The results are shown in Fig. 8.

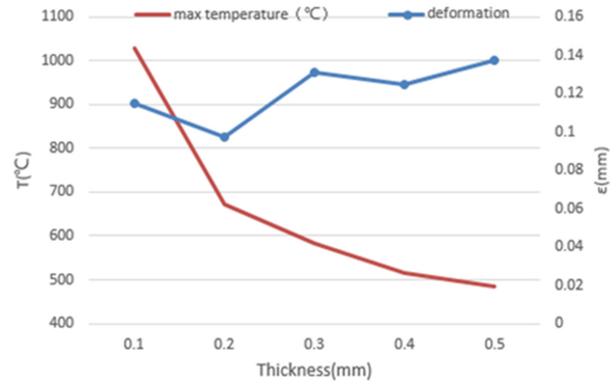

Figure 8: Maximum temperature and deformation of different thicknesses.

As the thickness increases, the maximum temperature decreases, but the deformation increases. Therefore, when we choose the thickness of the septum, we should also consider the structural properties and mechanical properties of the material.

Cooling Water Speed The rated pressure of the pump is 0.6 MPa, which can provides a cooling water speed of up to 1 m/s. Increasing the cooling water speed increases the heat exchange rate. According to the calculation equation of the pipeline resistance, the resistance of the cooling water is proportional to the square of the speed. As the resistance increases, the water cooling effect may change. We calculated the maximum temperature and deformation of the septum at different flow speeds and the results are shown in Fig. 9.

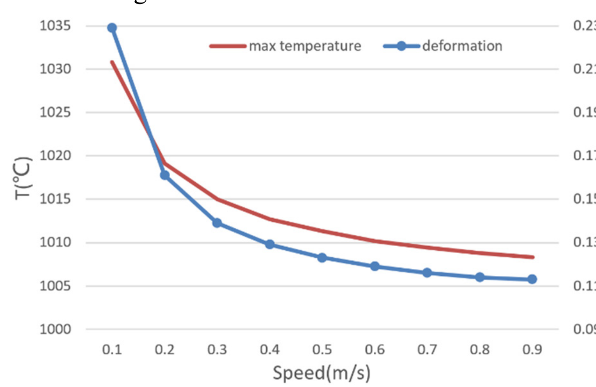

Figure 9: Maximum temperature and deformation of different water flow speeds.

CONCLUSION

This paper introduces the main structural design of the SC200 cyclotron electrostatic deflector and the fluid-solid coupling thermal analysis under extreme operating conditions. The actual work intensity will be lower than the simulation conditions. After analysis, a 0.1 mm thick tungsten septum may be a better choice. The simulation results will be compared to the experimental results at the end of this year.

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOP003

ACKNOWLEDGEMENT

Work supported by National Natural Science Foundation of China under grant No. 11775258 & 11575237, International Scientific and Technological Cooperation Project of Anhui grant No. 1704e1002207.

REFERENCES

[1] W. Wieszczycka and W. H. Scharf, "Proton radiotherapy accelerators", *World Scientific*, p. 344, August 2001. https://doi.org/10.1142/4617

[2] M. Re *et al.*, "Breakdown mechanisms in electrostatic deflector", in *Proc. 16th Int. Conf. on Cyclotrons and their Applications*, East Lansing, MI, USA, May 2001, p. 151.

[3] D. Poe *et al.*, "Status of electrostatic deflector at NSCL K1200 cyclotron", in *Proc. 15th Int. Conf. on Cyclotrons and their Applications*, Caen, France, Jun. 1998, pp. 229-231.

[4] J. DeKamp and F. Marti, "Thermo mechanical calculations of a cyclotron deflector", in *Proc. PAC'97*, Vancouver, Canada, May 1997, paper 8P022, p. 278.

[5] ANSYS, User's Guide Version 17.2, ANSYS Ltd., 2016.